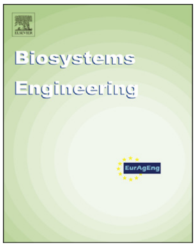
BIOSYSTEMS ENGINEERING 129 (2015) 370–377

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110



Research Paper

Effect of short rotation coppice plantation on the performance and chips quality of a self-propelled harvester

Vincenzo Civitarese [a], *Salvatore Faugno* [b,*], *Stefania Pindozzi* [b], *Alberto Assirelli* [a], *Luigi Pari* [a]

[a] *Consiglio per la ricerca e sperimentazione in Agricoltura, (Unità di ricerca per l'ingegneria agraria), Via della Pascolare n 16 00015, Monterotondo, Rome, Italy*
[b] *Department of Agriculture, University of Naples Federico II, Via Università 100, 80055 Portici, Naples, Italy*

ARTICLE INFO

Article history:
Received 23 May 2014
Received in revised form
7 October 2014
Accepted 12 November 2014
Published online 5 December 2014

Keywords:
Short Rotation Coppice
Harvesting performance
Biomass harvester
Dendrometric characteristic
Chipping

The performance of coppice harvesting machines is influenced by parameters such as field yield, the shape and size of the plantation and the space for turning at the headland. The quality of chips and the effect of the dendrometric characteristic of nine different species (*Fraxinus angustifolia, Robinia pseudoacacia, Salix alba, Eucalyptus occidentalis, Populus nigra* L. and four genotypes of *Populus x euroamericana* (Grimminge, Hoogvorst, Muur, Vesten) grown in the same flat plot of about 4.5 ha on the performance rate and quality of the work, was evaluated. Field yields ranged from 33 t ha^{-1} to ~95 t ha^{-1}, for the *S. alba* and *E. occidentalis*, respectively. The harvester worked with an average speed of 0.91 m s^{-1} (±0.22) and average productivities of 0.98 ha h^{-1} (±0.24) and 45.25 t h^{-1} (±5.56). There was a satisfactory linear correlation between the working speed of the machine and field yield. The quality of the chips showed some variability with values of moisture content ranging between 42.7% and 57.3% (for *R. pseudoacacia and S. Alba* respectively) and values of bulk density from 273 kg m^{-3} to 313 kg m^{-3} (for *Populus euroamericana* Vesten and *E. occidentalis* respectively).

© 2014 IAgrE. Published by Elsevier Ltd. All rights reserved.

1. Introduction

The aims of the European Union are to reduce 2020 greenhouse gas emissions to 80% of their 1990 emissions and to replace 20% of its final energy needs from renewable sources (Tol, 2012). This has led leading to an increasing interest in woody biomass for the production of biofuels, biochemicals, heat and electricity (Klass, 1998; Parikka, 2004; Van der Stelt, Gerhauser, Kiel, & Ptasinski, 2011; Zhu & Pan, 2010). Quaak, Knoef, and Stassen (1999) and McKendry (2002) affirmed that biomass represented a more sophisticated form of solar energy accumulation and it can be seen as a possible substitute to fossil fuels (Okello, Pindozzi, Faugno, & Boccia, 2013).

Rapidly growing trees are one of the most promising alternatives for the production of biomass when planted in a

---

* *Corresponding author.* Salvatore Faugno Department of Agriculture, University of Naples Federico II, Via Università 100, 80055 Portici, Naples, Italy. Tel. +39 081 2539148.
E-mail addresses: vincenzo.civitarese@entecra.it (V. Civitarese), faugno@unina.it (S. Faugno), stefania.pindozzi@unina.it (S. Pindozzi), alberto.assirelli@entecra.it (A. Assirelli), luigi.pari@entecra.it (L. Pari).

http://dx.doi.org/10.1016/j.biosystemseng.2014.11.009

1537-5110/© 2014 IAgrE. Published by Elsevier Ltd. All rights reserved.

Nomenclature

$\overline{M}$	Mean of measured data, m s^{-1}
Adjusted R^2	Adjusted coefficient of determination, dimensionless
D	Difference between simulated and measured value, m s^{-1}
EF	Efficiencies index, dimensionless
M	Measured value, m s^{-1}
MANOVA	Multivariate analysis of variance
n	Number of observations
odt	oven dry tons
OLS	Ordinary Least Squares
p(t)	Level of significance, dimensionless
S	Simulated value, m s^{-1}
SRC	Short rotation coppice
SRF	Short rotation forestry
x	Field yield in tons of fresh biomass per hectare, t ha^{-1}
y	Work speed, m s^{-1}
Subscripts	
i	ith observation

short rotation coppice (SRC) regime (Broeckx, Verlinden, Vangronsveld, & Ceulemans, 2012). Compared to other sources, dedicated crops show the highest yield in the shortest growing time (Alig, Adams, McCarl, & Ince, 2000). During the last ten years short rotation coppice has become more and more common in Italy with more than 4000 ha under cultivation, mostly located in the North of Italy (Spinelli, Nati, & Magagnotti, 2009), while the central and southern regions are cropped with small plots (Di Matteo, Sperandio, & Verani, 2012). Field yield of SRC plantations depends on the species considered, the genotype and on the characteristics of the sites. Genetic improvement programs within the EU have produced clones with high production rates for a wide range of climates and sites (Deckmyn, Muys, Garcia Quijano, Ceulemans, 2004; Liberloo, Calfapietra, Lukac, Godbold, Luos, et al., 2006). Species used include *Salix Alba*, *Fraxinus augustifolia*, *Eucalyptus occidentalis*, *Robinia pseudoacacia*, *Populus nigra*. The biomass produced by these energy crops are of low value and it is therefore necessary to obtain high yields (Verlinden, Broeckx, Van den Bulcke, Van Acker, & Ceulemans, 2013). Poplar (*Polulus* sp.) are one of the more suitable biomass crops for SRC in temperate regions (Bradshaw, Ceulemans, Davis, & Stettler, 2000) and many studies have shown that the annual yields between 3 and 20 t [dry matter] ha^{-1} (Ceulemans &Deraedt, 1999; Dillen, Marron, Bastien, Ricciotti, Salani, et al., 2007; Facciotto & Lioia, 2005; Mareschi, Paris, Sabatti, Nardin, Giovanardi, et al., 2005). Two different harvesting methods are generally used: *one phase*, with cutting and chipping simultaneously (Spinelli et al.,2009), operated with self-propelled chipper, and *two phases*, with cutting is done in winter, drying in the field and chipping in the following June (Pari et al., 2013). In order to make the SRF more profitable, and ensure sustainable cultivation, harvesting must be realised at high operational efficiency.

Field yield is one of the crop main variables to be taken into account when assessing the performance of a harvester (Handler & Blumauer, 2011), but other parameters can affect the machine performance such as the slope of the plot, shape and size of the plantation, the available space for turning in the headland, the bearing capacity of the soil at the harvesting time, machine power applied, trailer capacity and the experience of the staff and the methods used. For these reasons it is difficult to establish a direct relationship between work speed and field yield, unless comparative tests are conducted under similar operating conditions.

Harvesting tests of nine different species that grown as SRC, within a single flat area of about 4.5 ha were organised in April, 2013, at the experimental farm of Campania region “Improsta”, Italy. Harvesting was carried out over a single day using the same professional operators and machines in order to establish as similar as possible conditions for the duration of the test. The aim was to identify a correlation between the working speed of the harvester and the field yield of the different species of plantations, using data collected under similar conditions. The quality of the work done by the machine was also assessed as well as the quality of the chips obtained from different species by the same device.

2. Materials and methods

2.1. Site description and plantation layout

The SRC plantation was located in the Salerno province, Italy (40°33′32.18″N; 14°58′15.6″E) and consisted of different species and varieties that were planted in 2007 using both bare-root seedlings and cuttings (density of 6666 plants ha^{-1}). The crops harvested were: *Fraxinus angustifolia, Robinia pseudoacacia, Salix alba, E. occidentalis, P. nigra L.* and four genotypes of *Populus x euroamericana* (Grimminge, Hoogvorst, Muur, Vesten). The trees, first coppiced in 2010, were in their second three-year cutting cycle (roots were aged 6 yr and stems aged 3 yr R6S3). The total area harvested was ~4.50 ha but, in order to compare the performance of the harvesting machine, data collection (dendrometric surveys, working time measurements, etc.) was made on nine plots, one for each treatment, with a unit surface area of 840 m^2.

Before starting the tests, the effective density, the average number of shoots per plants, the height and the diameter of the main and secondary stems were measured at 100 mm from the ground, on 10 randomly chosen plants per plot. The total amount of biomass produced by each treatment was evaluated by weighing, on a certified scales, and the wood chips were blown into a trailer on each experimental plot.

2.2. Data collection

The machinery used for the trials were a Claas Jaguar self-propelled chipper 880 (nominal power of 370 kW), equipped with GBE-1 head, (Spinelli, Nati, & Magagnotti, 2008; Spinelli et al. 2009) and a Massey Ferguson 6497 Dyna-6 tractor (nominal power of 160 kW) coupled to a Zaccaria trailer with a capacity of 40 m^3. The drum chipper worked using only 12 of the 24 knives available, in order to avoid production of excessively fine chips. For each test, the machines were operated by the same driver.

The working times were recorded inside 45 transect, five per treatment, each of length 40 m, placed along the experimental plots previously identified. In order to ensure a better matching of the collected data, for each treatments, all the factors that were not strictly related to the machine-crop relationship, such as the average length of the row and the space for manoeuvre were excluded from the data. Machine productivity, therefore, was evaluated in terms of work speed ($m\ s^{-1}$) and harvesting productivity ($ha\ h^{-1}$ and $t\ h^{-1}$), excluding turns and delays. Quality of work was evaluated in terms of height of cut, number of stumps damaged and harvesting losses. The measurements were performed within five linear transects of 10 m for each treatments using the method of Mitchell (1997). Damage to the stumps was evaluated by measuring vertical cuts and fingerings according to the following rating scale: slight damage (1), medium damage (2), severe damage (3), stump destroyed (4). Harvesting losses were evaluated by collecting and weighing all the biomass left on the field at the end of the test.

2.3. *Wood chip characterisation*

Wood chips quality was evaluated by measuring the bulk density and moisture content according to EN 15103 and EN 14774-2, respectively. The bulk density was evaluated at the storage yard, by weighing 10 volumetric cylinder for each treatments. The cylinder used for the measurement had a ratio of height to diameter of 1.29, with a volume of 0.027 m^3. For the evaluation of the moisture content, 10 samples of 500 g, for each treatments, were dried in thermo-ventilated stove, at the temperature of 105°C ± 2 °C, until reaching a constant weight.

2.4. *Statistical analysis*

Dendrometrics data of the crops were analysed using a multivariate analysis of variance (MANOVA) using the free software PAST ver. 2.17b (Øyvind Hammer, Natural History Museum, University of Oslo–Norway). Data collected during the harvesting trials were used for estimating the performance of the machine as a function of the field productivity. The following regression models (linear, quadratic, cubic, and logarithmic) were tested using the software Statistica ver. 10 (StatSoft, Tulsa, Oklahoma–USA):

$$y_i = a + bx \quad i = 1, \ldots, n \tag{1}$$

$$y_i = a + bx^2 \quad i = 1, \ldots, n \tag{2}$$

$$y_i = a + bx^3 \quad i = 1, \ldots, n \tag{3}$$

$$y_i = a + \log x \quad i = 1, \ldots, n \tag{4}$$

where y is the work speed ($m\ s^{-1}$) and x is the field yield of fresh biomass per hectare ($t\ ha^{-1}$) and n is the number of observations. The parameters of the models were estimated by regression. A significance level of 5% was assumed. The performance of the four models was analysed and compared in terms of the agreement between measured data and predicted values (Confalonieri, Acutis, Bellocchi, & Donatelli, 2009; Pindozzi, Faugno, Okello, & Boccia, 2013). Several parameters were used to assess the performance of the models. The F-test parameters was used to evaluate the significance of the model, associated with a level of likelihood p (t) to evaluate the agreement between predicted and measured values. Other parameters were the efficiency of the model results to the mean of observations, and the Adjusted R-square. Modelling efficiencies index (*EF*) were calculated using

$$EF = 1 - \frac{\sum_{i=1}^{n} (D_i)^2}{\sum_{i=1}^{n} \left(M_i - \overline{M}\right)^2}, \tag{5}$$

where, n is the number of estimates; D_i is the difference between S_i and M_i, that are the ith simulated and the ith measured values, respectively; $\overline{M}$ is the mean of measured values. The maximum value of the index is 1 when there is a total agreement between the model and observed data. A value of 0 indicates that the predictive capacity of the model is equal to that of the mean value of the observed data, positive values indicates that the model is a better predictor than the average of observations. The minimum level is negative infinity ($-\infty$). The *EF* index is useful because it allows for the identification of inefficient models (Loague & Green, 1991). The data concerning the work and biomass quality were analysed by one-way ANOVA and Duncan's post hoc test. All statistics were computed by using the software Statistica ver. 10 (StatSoft, Tulsa, Oklahoma–USA).

3. Results

3.1. *Morphological characteristics*

The plants exhibited one main stems with different number of secondary shoots (Table 1). *P. nigra* and *R. pseudoacacia* showed the higher and the lower number of shoots, respectively. Considering the main stems, *E. occidentalis, P. x euroamericana* Hoogvorst, Muur and Vesten had the highest level of development, with average diameter higher than 60 mm and average height higher than 6 m.

The multivariate analysis (MANOVA) indicates the existence of statistically significant differences among the parameters of the species compared ($p < 0.001$). The pairwise comparison with Bonferroni corrected showed statistically significant differences for *R. pseudoacacia* towards all other crops and for *S. alba* towards *E. occidentalis*, *P. nigra* and *P. x Euro-American* Muur.

3.2. *Field yield and machine performances*

In Table 2 the fresh field yield and the oven dry mass of the different species was reported. The field yield ranged from 33 $t\ ha^{-1}$ to about 95 $t\ ha^{-1}$, for the *S. alba* and *E. occidentalis,* respectively. Among the poplars, *P. nigra* showed the highest productivity with 53 $t\ ha^{-1}$.

The performance of the self-propelled chipper varied as a function of the crop yield (Table 3). The machine worked with

Table 1 – Main dendrometric characteristic of the population.

Treatment	Species	Genotype	Diameter (mm)		Height (m)		n° of shoots
			Main stems	Secondary stems	Main stems	Secondary stems	
1	*P. x euroamericana*	Grimminge	51.50 ± 9.44	32.11 ± 8.2	4.92 ± 0.82	3.54 ±0.064	2.80 ± 0.63
2	*P. x euroamericana*	Hoogvorst	62.38 ± 11.25	35.47 ± 0.87	6.34 ± 0.78	4.04 ± 0.98	2.80 ± 0.42
3	*P. x euroamericana*	Muur	65.75 ± 10.92	31.42 ± 11.47	6.53 ± 0.66	4.23 ± 1.23	4.22 ± 1.39
4	*P. x euroamericana*	Vesten	67.2 ± 10.98	30.07 ± 12.88	6.25 ± 1.14	3.93 ± 1.01	2.50 ± 1.18
5	*P. nigra*	Limatola	53.64 ± 9.39	29.26 ± 12.47	5.91 ± 0.56	3.89 ± 1.18	4.50 ± 2.27
6	*S. alba*	–	47.63 ± 9.45	29.5 ± 7.86	4.18 ± 0.8	3.05 ± 0.78	3.80 ± 1.48
7	*F. oxyphylla*	–	50.83 ± 10.30	26.18 ± 9.56	5.27 ± 0.89	3.24 ± 0.89	3.40 ± 1.26
8	*E. occidentalis*	–	60.64 ± 15.68	29.95 ± 15.27	6.46 ± 1.52	3.99 ± 1.29	3.30 ± 1.70
9	*R. pseudoacacia*	–	36.40 ± 9.94	33.67 ± 9.29	5.12 ± 1.48	5.6 ± 1.23	1.30 ± 0.48

Table 2 – Yield at harvest (t ha^{-1}) and oven dry tons (odt) for the different treatments.

Treatment	Species	Genotype	Yield (t ha^{-1})	odt ha^{-1} year^{-1}
1	*P. x euroamericana*	Grimminge	35.38	5.60
2	*P. x euroamericana*	Hoogvorst	43.12	6.82
3	*P. x euroamericana*	Muur	46.35	7.27
4	*P. x euroamericana*	Vesten	37.64	6.16
5	*P. nigra*	Limatola	53.66	7.96
6	*S. alba*	–	33.45	4.77
7	*F. oxyphylla*	–	51.97	7.58
8	*E. occidentalis*	–	95.94	15.13
9	*R. pseudoacacia*	–	49.42	9.49

an average speed of 0.91 m s^{-1} (±0.22) and average productivities of 0.98 ha h^{-1} (±0.24) and 45.25 t h^{-1} (±5.56). The highest work speed was observed during the harvest of *P. x euroamerica* Grimminge. Significantly lower values were recorded during the harvest of *Eucalyptus* as a consequence of its high yield. On the other hand lower working speed was balanced by the higher value for hourly production.

The most accurate correlation between the working speed of the machine and field yield was achieved using a linear regression (Fig. 1, Table 4). This was confirmed by it having the highest EF Index (0.99) and a value of Adjusted R^2 of 0.90. The model considered the average value of field yield collected during the tests. In the model, the collection of *R. pseudoacacia* was not considered (treatment 9) because, the punctures to the tyres of the machine, caused by the secondary suckers across the raw, did not allow to collection data according to the methodology assessed.

The relationship reported in Fig. 1 allowed machine productivity as a function of the field yield to be calculated in a range from 30 to 90 t ha^{-1}. Considering an average field yield of 60 t ha^{-1}, the resulting work speed is of 0.87 m s^{-1} (3.1 km h^{-1}). This value decreased by 9.6%, 17.9% and 25.3%, when working with more productive planting, 70, 80 and 90 t ha^{-1}, respectively. The work speed increased, for plantations with 50, 40 and 30 t ha^{-1} by +11.4%, +25.3% and +43.2%, respectively.

A second model was implemented using only the data collected during the harvesting of poplar (treatments 1, 2, 3, 4, 5); that is one of the species most widely used in Italy for SRC plantations. The statistical analysis showed the best fit was obtained by the logarithmic model (adjusted R^2 0.93, EF 0.94) (Fig. 2, Table 5). Using the equation reported in Fig. 2 it was possible to obtain specific references on the working speed of the machine during the harvesting by considering a range of productivity between 40 and 55 t ha^{-1}.

Table 3 – Operative parameters of the self-propelled chipper.

Treatment	Species	Genotype	x	y	Machine productivity	
			t ha^{-1}	m s^{-1}	ha h^{-1}	t h^{-1}
1	*P. x euroamericana*	Grimminge	35.38	1.17	1.27	44.93
2	*P. x euroamericana*	Hoogvorst	43.12	1.02	1.1	47.43
3	*P. x euroamericana*	Muur	46.36	0.99	1.07	49.6
4	*P. x euroamericana*	Vesten	37.64	1.11	1.2	45.17
5	*P. nigra*	Limatola	53.66	0.95	1.02	54.73
6	*S. alba*	–	33.45	1	1.08	36.13
7	*F. oxyphylla*	–	51.97	0.83	0.9	46.77
8	*E. occidentalis*	–	95.93	0.43	0.46	44.13
9	*R. pseudoacacia*	–	–	–	–	–

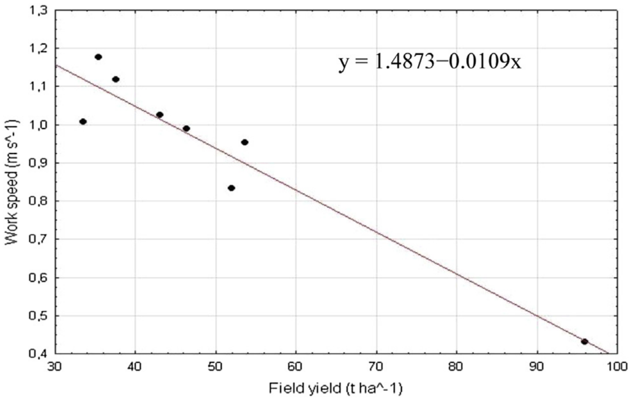


Fig. 1 – Relationship between field yield (t ha^{-1}) and work speed (m s^{-1}) according to linear regression model.

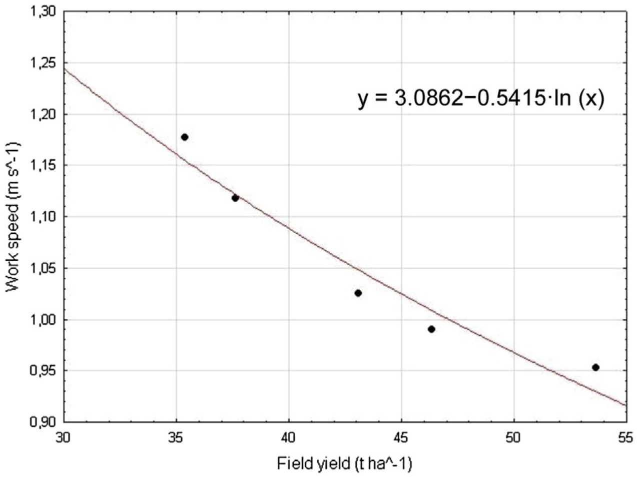


Fig. 2 – Relationship between field yield (t ha^{-1}) and work speed (m s^{-1}) according to logarithmic regression model.

3.3. *Quality of work performed by the self-propelled chipper*

Harvesting losses in the field were limited and always <0.60% of the total crop, confirming the functionality of the header with trees characterised by different morphology. The cut height ranged between 63 mm and 108 mm, these values, are in line with the optimal height of work of the machine. Damage of the stumps (Table 6) showed great variability in the data collected. The *P. x euroamericana* Hoogvorst showed a greater tendency to fraying than the other treatments (22.46%), followed by *S. Alba* (15.74%), that had the higher percentage of vertical cut (12.76%). Such damages are generally produced during the initial stages of contact of the cutting elements with the trees. One way ANOVA showed no statistically significant differences between the various species compared and have not been detected significant correlations between observed damage and operating parameters of the machine. Most of the damages, however, having been classified as minor, are not capable to compromise the lifetime of the stumps.

3.4. *Chip quality*

Moisture content of the biomass ranged between 42.7% and 57.3%, for black locust and willow, respectively. The analysis proved the existence of statistically significant differences in moisture content among the following species: *P. x euroamericana* Vesten, *P. nigra L*, *E. occidentalis* and *P. x euroamericana* Grimminge, Hoogvorst and Muur. On the other hand, there were no significant differences among *P. nigra L*, *S. alba* and *F. angustifolia*. Finally *R. pseudoacacia* differs from all other species considered (Fig. 3).

As for the moisture content, the bulk density has a certain variability depending on the different treatment considered, with values ranging from 273 kg m^{-3} to 313 kg m^{-3}, for the *P. x euroamericana* Vesten and *E. occidentalis*, respectively. There were no statistically significant differences between *R. Pseudoacacia*, *S. alba*, *P. nigra L.* and *P. x euroamericana* Vesten, Muur and Hoogvorst. The bulk density of the *P. x euroamericana* Grimminge were statistically different from the previous treatments, but not from each other, while the *E. occidentalis* differs significantly from all other species (Fig. 4).

4. Discussion

According to Schweier and Becker (2012b) the performance of harvesting machines significantly depends on the biomass per hectare, whilst other parameters, such as the dendrometric characteristics of the trees, are not statistically significant. Many authors have reported results on machine performance during SRC harvesting tests confirming great variability in values obtained (Fiala & Bacenetti, 2012; Schweier & Becker, 2012a; Spinelli et al., 2008).

Biomass plantations are characterised by regular planting distance, with number and average length of the rows known or easily detectable. Once assessed the field yield is possible to evaluate the effective harvesting time by dividing the total linear length of the rows (No. of rows × average length of the

Table 4 – Model 1: OLS, Relationship type: y = a + bx, where y is the Work speed (m s^{-1}), *x* is Field yield (t ha^{-1}), obs 1–8, R^2 = 0.90, EF = 0.9998.

Relationship type: y = a + bx	Coefficient	Std Error	t- value	*p*-value	
a	1.487336	0.071809	20.71237	<0.001	***
b	−0.010984	0.001352	−8.12610	<0.001	***

*** Significance at level *p* = 0.1.

Table 5 – Model 2: OLS, Relationship type: $y = a + b \ln(x)$, where y is the Work speed ($m\ s^{-1}$), x is Field Yield ($t\ ha^{-1}$), obs 1–5, $R^2 = 0.93$, EF = 0.94.

Relationship type: $y = a + b \ln(x)$	Coefficient	Std Error	t- value	*p*-value	
a	3.08628	0.280474	11.00377	0.001	***
b	−0.541578	0.074627	−7.25728	0.005	*

* Significant at $p = 0.05$; *** Significant at $p = 0.01$.

rows) by the working speed calculated through the two models developed (Figs. 3 and 4). The scheduled work time can be estimated considering, as indicated by Spinelli et al., (2009), an average end-row turn time corresponding to 0.55 min per occurrence and a 20% of the total worksite time for maintenance, waiting, rest and delays times.

The moisture content of biomass, ranging from 42.7 % to 57.3 %, for *R. pseudoacacia* and *S. alba* respectively, is in line with results reported in other studies on field performance of SRF in Italy (Buratti, Costarelli, Cotana, Crisostomi, & Fantozzi, 2005; Di Matteo et al., 2012). These data suggest the possibility of mixing wood chips of different species, as a function of the average moisture level to be obtained, in order to improve the overall efficiency of biomass combustion process.

As for the moisture content, the bulk density has a certain variability depending on the different treatment considered, with values ranging from 273 kg m^{-3} to 313 kg m^{-3}, for the *P. x euroamericana* Vesten and *E. occidentalis*, respectively. The variability of bulk density is reported in literature data as well, since it is affected by harvest techniques, like chipping and compaction (Kauter, Lewandowski, & Claupein, 2003). Generally chips have a relatively low bulk density, around 250 kg m^{-3} (Hamelinck, Suurs, & Faaij, 2005), i.e. 2–3 times lower than reported after a densification process (Eriksson & Prior, 1990).

The total amount of biomass that is possible to transport, with the same volume, is directly proportional to the bulk density of the wood chip produced. *P. x euroamericana* Grimminge and Vesten show a very similar yield at harvest (about 35 t ha^{-1}) but the different values of bulk density, are 298 kg m^{-3} and 273 kg m^{-3}, respectively. This difference would lead to a greater number of transport vehicles circulating on the road considering genotype Vesten, which is about one

Table 6 – Percentage distribution of the damage to the stumps.

Treatment	Species	Genotype	Frying (%)				Vertical cut (%)			
			1	2	3	4	1	2	3	4
1	*P. x euroamericana*	Grimminge	11.68	1.54	–	–	3.96	–	–	–
2	*P. x euroamericana*	Hoogvorst	22.46	–	–	–	3.93	–	–	
3	*P. x euroamericana*	Muur	10.35	–	–	–	–	–	–	–
4	*P. x euroamericana*	Vesten	8.51	1.33	4.30	–	–	–	–	–
5	*P. nigra*	Limatola	8.86	1.54	–	–	6.96	–	–	–
6	*S. alba*	–	15.74	1.11	–	–	12.76	–	–	–
7	*F. oxyphylla*	–	11.01	3.46	–	–	2.22	1.11	–	–
8	*E. occidentalis*	–	10.61	1.18	–	–	5.89	6.25	–	–
9	*R. pseudoacacia*	–	12.31	1.05	2.11	–	5.03	–	–	–

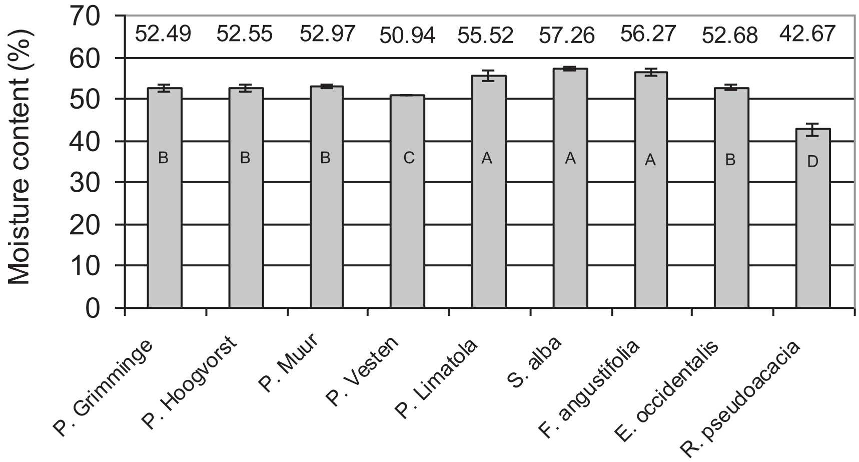


Fig. 3 – Moisture content of the biomass for the different species considered. Welch F test: df: 7.593, F: 80.7 p: 0.000*. Duncan's post hoc test: different letters indicate statistically significant differences.

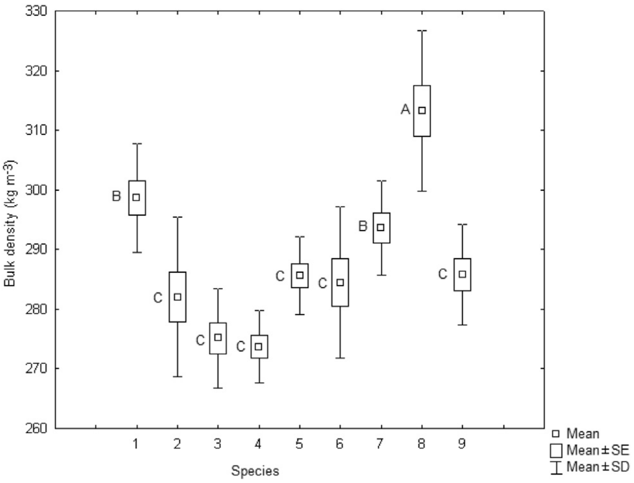


Fig. 4 – Bulk density of the wood chips for the different treatments. Welch F test: df: 36.35, F: 17.97 p: 0.000*”. Duncan's post hoc test: different letters indicate statistically significant differences.

truck of 80 m^3 of capacity for every 8 ha of plantation. In terms of energy districts (with areas of hundreds of hectares) the environmental, economic and logistic impacts becomes evident. Since the two species have the same harvesting yields, it would be preferable to establish the plantations of the genotype Grimminge.

Chips obtained from SRC with “3 years” harvesting interval represent a good fuel as indicated in a study conducted by Picchio et al. (2012) on four different clones of poplar (AF6, AF2, Monviso, Muur).

Further investigations will be extended for proximate and ultimate analysis to define particle size distribution, ash content, the heating value, content of Carbon, Nitrogen and Hydrogen of the biomasses collected during the tests.

5. Conclusions

The performances of the self-propelled chipper were analysed in a plantations of SRF, where different woody crops were developed at different rates of growth. The models proposed allow to predict the operability of the harvesting machine as a function of a large range of yield levels. The higher correlation indicates that the effective working capacity is mostly explained by the field productivity as confirmed by the efficiency index that was higher for a linear model. Harvesting being one of the main phases in the productivity process, the possibility to assess the time required to complete the harvesting process is a fundamental parameter for a correct and careful scheduling of activities. Some quality parameters of the woody chips, such as the moisture content and the bulk density, can vary considerably from species to species, affecting transportation costs, boiler efficiency, time for deliveries and, generally, the overall balance of the whole energy chain. For this reason stakeholders should weight these parameters when technical choices have to be made.

Acknowledgements

This research was realized under PON Project 01_01966 “Integrated agro-industrial chains with high energy efficiency for the development of eco-compatible processes of energy and bio-chemicals production from renewable sources and for the land valorisation (ENERBIOCHEM)” funded by Italian Ministry of Education, University and Research.

REFERENCES

Alig, R. J., Adams, D. M., McCarl, B. A., & Ince, P. J. (2000). Economic potential of short-rotation woody crops on agricultural land for pulp fiber production in the United States. *Forest Products Journal, 50*(5).

Bradshaw, H. D., Ceulemans, R., Davis, J., & Stettler, R. (2000). Emerging model systems in plant biology: poplar (Populus) as a model forest tree. *Journal of Plant Growth Regulation, 19*(3), 306–313.

Broeckx, L. S., Verlinden, M. S., Vangronsveld, J., & Ceulemans, R. (2012). Importance of crown architecture for leaf area index of different Populus genotypes in a high-density plantation. *Tree Physiology, 32*(10), 1214–1226.

Buratti, C., Costarelli, I., Cotana, F., Crisostomi, L., & Fantozzi, F. (2005). The biomass research centre laboratory for biomass characterization. In *Proceedings of 14th European Biomass Conference and Exhibition. Biomass for Energy, Industry and Climate Protection. Paris* (pp. 17–21).

Ceulemans, R., & Deraedt, W. (1999). Production physiology and growth potential of poplars under short-rotation forestry culture. *Forest Ecology and Management, 121*(1), 9–23.

Confalonieri, R., Acutis, M., Bellocchi, G., & Donatelli, M. (2009). Multi-metric evaluation of the models WARM, CropSyst, and WOFOST for rice. *Ecological Modelling, 220*(11), 1395–1410.

Deckmyn, G., Muys, B., Garcia Quijano, J., & Ceulemans, R. (2004). Carbon sequestration following afforestation of agricultural soils: comparing oak/beech forest to short-rotation poplar coppice combining a process and a carbon accounting model. *Global Change Biology, 10*(9), 1482–1491.

Di Matteo, G., Sperandio, G., & Verani, S. (2012). Field performance of poplar for bioenergy in southern Europe after two coppicing rotations: effects of clone and planting density. *iForest-Biogeosciences & Forestry, 5*(5).

Dillen, S. Y., Marron, N., Bastien, C., Ricciotti, L., Salani, F., Sabatti, M., et al. (2007). Effects of environment and progeny on biomass estimations of five hybrid poplar families grown at three contrasting sites across Europe. *Forest Ecology and Management, 252*(1), 12–23.

Facciotto, G., & Lioia, C. (2005). Biomasse legnose, alternativa ecologica ed economica al petrolio. Cross. In *Compliance – Coltiviamo energia e produciamo ambiente: Nuove possibilità di reddito per l'agricoltura piemontese, Cuneo, 24 Giugno 2005. [It]*.

Fiala, M., & Bacenetti, J. (2012). Economic, energetic and environmental impact in short rotation coppice harvesting operations. *Biomass and Bioenergy, 42*, 107–113.

Hamelinck, C. N., Suurs, R. A., & Faaij, A. P. (2005). International bioenergy transport costs and energy balance. *Biomass and Bioenergy, 29*(2), 114–134.

Kauter, D., Lewandowski, I., & Claupein, W. (2003). Quantity and quality of harvestable biomass from Populus short rotation coppice for solid fuel use—a review of the physiological basis and management influences. *Biomass and Bioenergy, 24*(6), 411–427.

Klass, D. L. (1998). *Biomass for renewable energy, fuels, and chemicals* (1st ed.). San Diego CA: Academic press.

Liberloo, M., Calfapietra, C., Lukac, M., Godbold, D., Luos, Z. B., Polle, A., et al. (2006). Woody biomass production during the second rotation of a bio-energy Populus plantation increases in a future high CO2 world. *Global Change Biology, 12*(6), 1094–1106.

Loague, K., & Green, R. E. (1991). Statistical and graphical methods for evaluating solute transport models: overview and application. *Journal of Contaminant Hydrology, 7*(1), 51–73.

Mareschi, L., Paris, P., Sabatti, M., Nardin, F., Giovanardi, R., Manazzone, S., et al. (2005). Le nuove varietà di pioppo da biomassa garantiscono produttività interessanti. *L'Informatore Agrario, 18*, 49–53 [It].

McKendry, P. (2002). Energy production from biomass (part 1): overview of biomass. *Bioresource Technology, 83*(1), 37–46.

Mitchell, T. M. (1997). *Machine learning, 45*. Burr Ridge, IL: McGraw Hill.

Okello, C., Pindozzi, S., Faugno, S., & Boccia, L. (2013). Development of bioenergy technologies in Uganda: a review of progress. *Renewable and Sustainable Energy Reviews, 18*, 55–63.

Pari, L., Civitarese, V., Giudice, A. D., Assirelli, A., Spinelli, R., & Santangelo, E. (2013). Influence of chipping device and storage method on the quality of SRC poplar biomass. *Biomass and Bioenergy, 51*, 169–176.

Parikka, M. (2004). Global biomass fuel resources. *Biomass and Bioenergy, 27*(6), 613–620.

Picchio, R., Spina, R., Sirna, A., Lo Monaco, A., Civitarese, V., Del Giudice, A., et al. (2012). Characterization of woodchips for energy from forestry and agroforestry production. *Energies, 5*, 3803–3816.

Pindozzi, S., Faugno, S., Okello, C., & Boccia, L. (2013). Measurement and prediction of buffalo manure evaporation in the farmyard to improve farm management. *Biosystems Engineering, 115*(2), 117–124.

Quaak, P., Knoef, H., & Stassen, H. E. (1999). *Energy from biomass: A review of combustion and gasification technologies* (Vol. 23). World Bank Publications.

Schweier, J., & Becker, G. (2012a). Harvesting of short rotation coppice – harvesting trials with a cut and storage system in Germany. *Silva Fennica, 46*(2), 287–299.

Schweier, J., & Becker, G. (2012b). New Holland forage Harvester's productivity in short rotation coppice: evaluation of field studies from a German perspective. *International Journal of Forest Engineering, 23*, 82–88.

Spinelli, R., Nati, C., & Magagnotti, N. (2008). Harvesting short-rotation poplar plantations for biomass production. *Croatian Journal of Forest Engineering, 29*(2), 129–139.

Spinelli, R., Nati, C., & Magagnotti, N. (2009). Using modified foragers to harvest short-rotation poplar plantations. *Biomass and Bioenergy, 33*(5), 817–821.

Tol, R. S. (2012). A cost–benefit analysis of the EU 20/20/2020 package. *Energy Policy, 49*, 288–295.

Van der Stelt, M. J. C., Gerhauser, H., Kiel, J. H. A., & Ptasinski, K. J. (2011). Biomass upgrading by torrefaction for the production of biofuels: a review. *Biomass and Bioenergy, 35*(9), 3748–3762.

Verlinden, M. S., Broeckx, L. S., Van den Bulcke, J., Van Acker, J., & Ceulemans, R. (2013). Comparative study of biomass determinants of 12 poplar (*Populus*) genotypes in a high-density short-rotation culture. *Forest Ecology and Management, 307*, 101–111.

Zhu, J. Y., & Pan, X. J. (2010). Woody biomass pretreatment for cellulosic ethanol production: technology and energy consumption evaluation. *Bioresource Technology, 101*(13), 4992–5002.

WEB REFERENCES

Eriksson, S., & Prior, M. (1990). *The briquetting of agricultural wastes for fuel*. Rome, Italy: Food and Agriculture Organization of the United Nations (UN FAO). Available at http://www.fao.org/docrep/T0275E/T0275E00.htm Accessed 04.14.

Handler, F., & Blumauer, E. (2011). *Logistic chains for wood chips from short rotation forestry*. http://www.blt.bmlfuw.gv.at/vero/veroeff/1203_Logistics_chains_for_wood_chips_from_short_rotation_forestry.pdf Accessed 23.04.14.